

Sensitivity Analysis and Evaluation of MicroFacPM: A Microscale Motor Vehicle Emission Factor Model for Particulate Matter Emissions

Rakesh B. Singh

National Research Council Research Associate, National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC

Alan H. Huber

National Atmospheric and Oceanic Administration, Atmospheric Sciences Modeling Division, in partnership with U.S. Environmental Protection Agency, National Exposure Research Laboratory, Research Triangle Park, NC

James N. Braddock

National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC

ABSTRACT

A microscale emission factor model (MicroFacPM) for predicting real-time site-specific motor vehicle particulate matter emissions was presented in the companion paper titled "Development of a Microscale Emission Factor Model for Particulate Matter (MicroFacPM) for Predicting Real-Time Motor Vehicle Emissions." The emission rates discussed are in mass per unit distance with the model providing estimates of fine particulate matter (PM_{2.5}) and coarse particulate matter. This paper complements the companion paper by presenting a sensitivity analysis of the model to input variables and evaluation model outputs using data from limited field studies. The sensitivity analysis has shown that MicroFacPM emission estimates are very sensitive to vehicle fleet composition, speed, and the percentage of high-emitting vehicles. The vehicle fleet composition can affect fleet emission rates from 8 mg/mi to 1215 mg/mi; an increase of 5% in the smoking (high-emitting) current average U.S. light-duty vehicle fleet (compared with 0%) increased PM_{2.5} emission rates by

~272% for 2000; and for the current U.S. fleet, PM_{2.5} emission rates are reduced by a factor of ~0.64 for speeds >50 miles per hour (mph) relative to a speed of 10 mph. MicroFacPM can also be applied to examine the contribution of emission rates per vehicle class, model year, and sources of PM. The model evaluation is presented for the Tuscarora Mountain Tunnel, Pennsylvania Turnpike, PA, and some limited evaluations at two locations: Sepulveda Tunnel, Los Angeles, CA, and Van Nuys Tunnel, Van Nuys, CA. In general, the performance of MicroFacPM has shown very encouraging results.

INTRODUCTION

We described previously the development of a microscale emission factor model for particulate matter (MicroFacPM) for predicting real-time motor vehicle emissions.¹ Although the toxicological response of inhaled particles also depends on the particle properties, such as size, number, active surface area, concentration, physical and chemical characteristics, and solid versus liquid phase, very limited information is available on particulate emission rates except mass-based emission factors. Therefore, emission rates will be discussed in mass per unit distance. The algorithm used to calculate emission factors in MicroFacPM is disaggregated and is based on the actual on-road vehicle fleet and calculates emission rates from a real-time site-specific fleet. The model requires only a few input variables to characterize the real-time fleet. The primary variables required are the description or characterization of on-road vehicle fleet, time and day of the year, ambient temperature, relative humidity (RH), and the percentage of high particulate matter (PM)-emitting vehicles in the fleet. A speed correction factor is calculated for speeds other than 19.6 miles per hour (mph) for heavy-duty diesel vehicles. A fuel additive correction factor is accounted for if oxygenated fuel is used. The cold

IMPLICATIONS

Current motor vehicle particulate emission models are designed to estimate county-level emission factors and associated emission inventories. These models are not reliable for real-time emission estimates needed to support human exposure studies. MicroFacPM is designed to estimate emission factors for the US motor vehicle fleet and is suitable for estimating real-time emission factors in microenvironments of human exposure near roadways. This approach is a useful tool for modeling human exposure microenvironments in vehicles and near roadways and for understanding complex relationships between roadway fixed-site ambient monitoring data and actual human exposure.

engine correction factor is calculated for vehicles running with cold engines based on their trip length and ambient temperature. The air conditioning (A/C) correction factor for light-duty gasoline vehicles (LDGVs) is applied for the apparent temperatures (heat index) >65 °F.

As discussed in the previous paper,¹ current PM emission models, MOBILE6 (now PART and MOBILE6 are merged in the version MOBILE6.2; used in the United States, except California) and the EMFAC Emissions Factors Model (used in California only), are designed to estimate regional (county) scale modeling and emission inventories and are not reliable to estimate real-time emissions needed for human exposure studies near roadways. MicroFacPM is developed using the latest information on PM emissions from several sources. Primary emission rates are calculated per vehicle type and model year based on their emission categories (normal and high-emitting). MicroFacPM first calculates the fraction of vehicles in each category for a 25-yr age-wise distribution and then groups these into either normal or high-emitting vehicles. Then, the vehicle miles accumulated for each vehicle are calculated based on the model year. The vehicle miles accumulated are used to calculate primary normal emission rates in milligrams per mile for heavy-duty diesel vehicles (weighing >8500 lb). MicroFacPM then calculates various correction factors based on the vehicle type, model year, and emission level. Finally, corrected emission rates for individual vehicles are calculated and multiplied by the fraction of vehicles of each model year and vehicle class. The sum of these yields a composite emission factor for the on-road vehicle fleet:

$$CEF = \sum_{i,j} ER_{i,j} \times VEH_{i,j} \quad (1)$$

where *CEF* is the composite emission factor, *ER_{i,j}* is the composite emission rate for vehicle type *i* and model year *j*, and *VEH_{i,j}* is the fraction of vehicles for vehicle type *i* and model year *j*.

This paper discusses sensitivity analysis for the model and evaluation of the model under operational conditions in the United States using data from the Tuscarora Mountain Tunnel, Pennsylvania Turnpike, PA. An additional limited evaluation at two other locations, Sepulveda Tunnel, Los Angeles, CA, and Van Nuys Tunnel, Van Nuys, CA, is also presented. The sensitivity analysis is first provided to understand the importance of the model input variables.

SENSITIVITY ANALYSIS

The degree of uncertainty in the real world can be assessed by performing sensitivity analysis of the model. Sensitivity analysis is an important tool to examine model performance in the presence of uncertainty in the model input variables. The schematic diagram of MicroFacPM input variables used to calculate the on-road site-specific vehicle fleet is displayed in Figure 1a. The schematic diagram for calculating correction factors for primary emission rates is depicted in Figure 1b. This section discusses the sensitivity of emission estimates to the input parameters of the vehicle fleet composition, speed, ambient

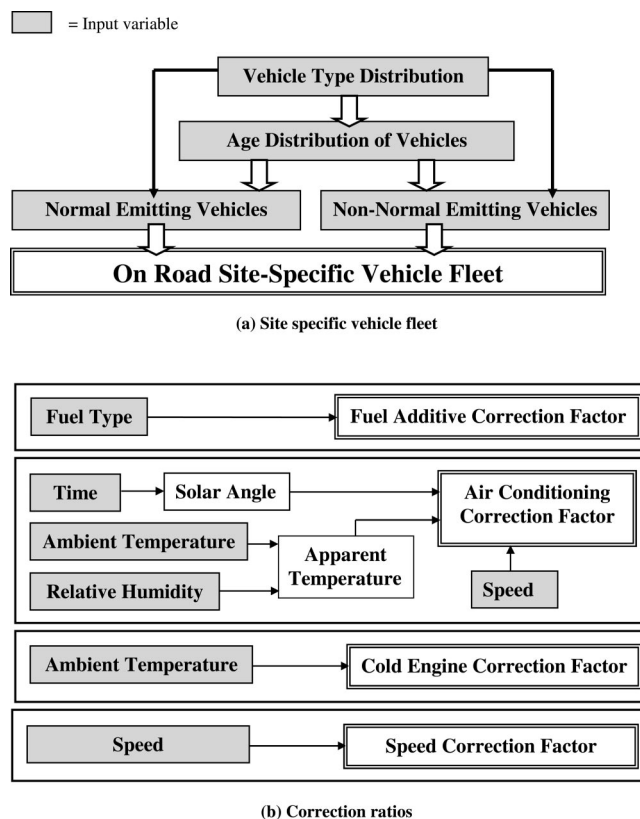


Figure 1. Schematic diagram of MicroFacPM input variables used to calculate (a) site-specific vehicle fleet and (b) correction factors.

temperature, RH, and percentage of smoking (high-emitting) vehicles. The sensitivity is performed assuming that all of the input parameters are independent variables, which do not affect each other. Sensitivity analysis for the model input parameters was carried out assuming the average U.S. vehicle fleet make-up for 1996.^{2,3} The model was run for the vehicle fleet in July 1, 2000. The vehicle classification used in MicroFacPM along with the abbreviation is given in Table 1, which is similar to that used in MOBILE6, the vehicle emission modeling software of U.S. Environmental Protection Agency (EPA)³ and MicroFacCO, the micro-scale emission factor model for North American vehicles for carbon monoxide.⁴ Average vehicle classes and age distribution of the U.S. vehicle fleet is presented in Figure 2.^{2,3} Light-duty vehicles were ~93.7% of the total fleet (Figure 2a). The gasoline-engine vehicles in the fleet consisted 99.3% of light-duty vehicles (<8500 lb) and 56.5% of heavy-duty vehicles (>8500 lb). The age distribution of the vehicles is presented in Figure 2b. Average ages for light-duty vehicle, light-duty truck (LDT)12 (LDT1 and LDT2), LDT34 (LDT3 and LDT4), heavy-duty vehicle (HDV)2B3 (HDV2B and HDV3), HDV48 (HDV4, HDV5, HDV6, HDV7, and HDV8), heavy-duty school buses, and heavy-duty transit buses were 8.6, 8.7, 10.6, 9.5, 11, 11, and 9.5 yr, respectively.

The input variables used to calculate the on-road site-specific vehicle fleet and the correction factors for the primary emission rates in MicroFacPM are similar to those for MicroFacCO,^{4,5} except for the percentage of smoking vehicles (in case of MicroFacCO this variable was "tailpipe emission standards noncompliance rate"). A key factor in

Table 1. Vehicle classification used in MicroFacPM.

SN	Description	Gross Vehicle Weight (lb)	Symbol	Class
Light-duty vehicles				
Gasoline vehicles				
1	Light-duty gasoline vehicles (cars)	0–6000	LDGV	LDV
2	Light-duty gasoline trucks 1	0–3750	LDGT1	LDT12
3	Light-duty gasoline trucks 2	3750–6000	LDGT2	LDT12
4	Light-duty gasoline trucks 3	6001–7250	LDGT3	LDT34
5	Light-duty gasoline trucks 4	7251–8500	LDGT4	LDT34
6	Motor cycles	All	MC	MC
Diesel vehicles				
7	Light-duty diesel vehicles (cars)	0–6000	LDDV	LDV
8	Light-duty diesel trucks 1	0–3750	LDDT1	LDT12
9	Light-duty diesel trucks 2	3750–6000	LDDT2	LDT12
10	Light-duty diesel trucks 3	6001–7250	LDDT3	LDT34
11	Light-duty diesel trucks 4	7251–8500	LDDT4	LDT34
Heavy-duty vehicles				
Gasoline vehicles				
12	Heavy-duty gasoline vehicles class 2B	8501–10,000	HDGV2B	HDV2B5
13	Heavy-duty gasoline vehicles class 3	10,001–14,000	HDGV3	HDV2B5
14	Heavy-duty gasoline vehicles class 4	14,001–16,000	HDGV4	HDV2B5
15	Heavy-duty gasoline vehicles class 5	16,001–19,500	HDGV5	HDV2B5
16	Heavy-duty gasoline vehicles class 6	19,501–26,000	HDGV6	HDV67
17	Heavy-duty gasoline vehicles class 7	26,001–33,000	HDGV7	HDV67
18	Heavy-duty gasoline vehicles class 8A	33,001–60,000	HDGV8A	HDV8
19	Heavy-duty gasoline vehicles class 8B	>60,000	HDGV8B	HDV8
20	Heavy-duty gasoline school bus	All	HDGSB	HDB
21	Heavy-duty gasoline transit bus	All	HDGTB	HDB
Diesel vehicles				
22	Heavy-duty diesel vehicles class 2B	8501–10,000	HDDV2B	HDV2B5
23	Heavy-duty diesel vehicles class 3	10,001–14,000	HDDV3	HDV2B5
24	Heavy-duty diesel vehicles class 4	14,001–16,000	HDDV4	HDV2B5
25	Heavy-duty diesel vehicles class 5	16,001–19,500	HDDV5	HDV2B5
26	Heavy-duty diesel vehicles class 6	19,501–26,000	HDDV6	HDV67
27	Heavy-duty diesel vehicles class 7	26,001–33,000	HDDV7	HDV67
28	Heavy-duty diesel vehicles class 8A	33,001–60,000	HDDV8A	HDV8
29	Heavy-duty diesel vehicles class 8B	>60,000	HDDV8B	HDV8
30	Heavy-duty diesel school bus	All	HDDSB	HDB
31	Heavy-duty diesel transit bus	All	HDDTB	HDB

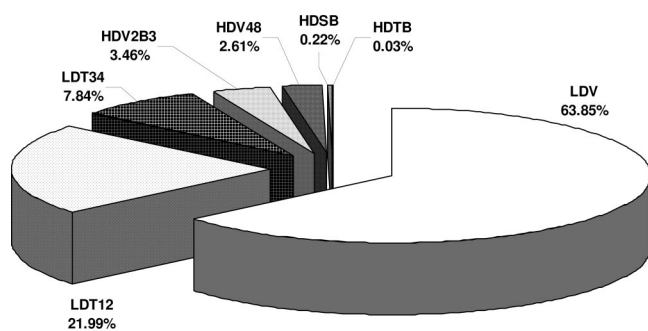
Notes: If more than one vehicle class is combined, then they are represented by a symbol showing combination. For example, HDGV2B and HDGV3 are represented as HDGV2B3; or HDGV4, HDGV5, HDGV6, HDGV7, HDGV8A, and HDGV8B are represented as HDGV48.

estimating emissions is how well the traffic fleet is characterized. The cold mileage percentage (fraction of distance traveled with cold start) is calculated assuming the same length of trip as used in MOBILE6. The sensitivity analysis is conducted for the following input “variables”: date of July 1, 2000; time of 10:00 a.m. local; vehicle fleet of the average U.S. fleet make-up; ambient temperature of 75 °F; average speed of 19.6 mph; atmospheric RH of 50%; cold mileage option; nonoxygenated fuel; and smoking vehicle percentage of 1%.

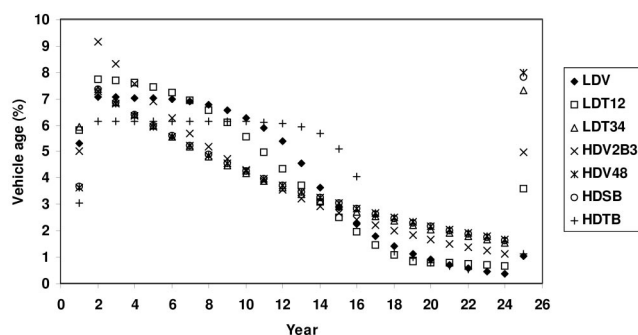
Vehicle Fleet Composition

The vehicle fleet composition has a large effect on PM composite estimated emission rates. Comparisons of PM_{2.5} emission rates from MicroFacPM for the U.S. gasoline vehicle fleet, diesel vehicle fleet, and year-wise vehicle fleet are shown in Figure 3. The model was run at 19.6 mph, 75 °F, consisting of average U.S. average distribution. The distribution of estimated emission rates for the

vehicle fleet varies widely, ranging from 8 mg/mi (LDGV) to 1215 mg/mi (HDDTB [heavy-duty diesel transit buses]). The principal factor accounting for this variation is vehicle fuel type; the composite estimated emission rates for gasoline vehicles range between 8 mg/mi and 31 mg/mi (Figure 3a), and those for diesel vehicles range between 216 mg/mi and 1215 mg/mi (Figure 3b). The age distribution of estimated emission rates for the U.S. vehicle fleet is compared in Figure 3c. The age of the fleet for U.S. average vehicle fleet also has a dramatic effect on estimated emission rates, ranging from 14 mg/mi (new vehicles) to 130 mg/mi (older vehicles). Therefore, it is clear that the precise on-road vehicle fleet composition is very important in calculating a reliable composite emission factor. Note that the estimated emission rates in Figure 3 include the cold running emissions. If we compare estimated emission rates from hot running gasoline cars only, then one normal emitting old car (pre-1981) is approximately equal to 69 normal emitting new cars (tier 1:



(a) Average class distribution for the USA vehicle fleet



(b) Average age distribution for the USA vehicle fleet (year 25 indicates vehicles >25 years old)

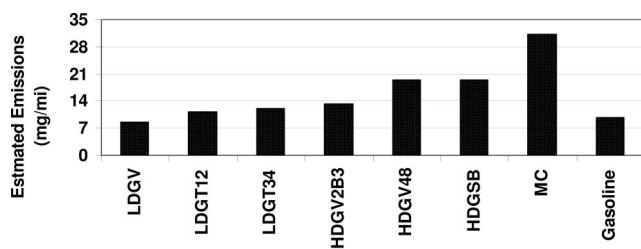
Figure 2. Average vehicle class (a) and age distribution (b) of U.S. vehicle fleet used in MicroFacPM for July 1, 2000.

1993+) and one smoking car (all ages) is approximately equal to 17 pre-1981 normal emitter cars or 1173 tier 1 normal emitter cars.

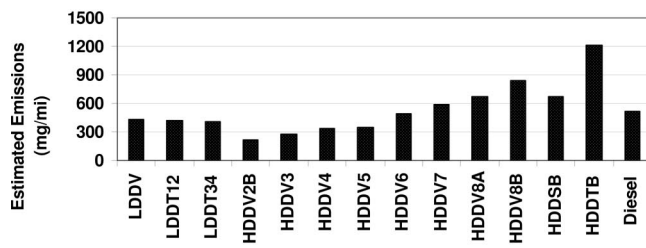
Speed

Speed of the vehicle affects estimated emissions rates in two ways: the speed correction factor and the A/C correction factor (Figure 2b). The effect of speed on U.S. gasoline, diesel, and average vehicle fleet (composite) is shown in Figure 4a. There is negligible change in estimated PM emission rates with the change in speed for gasoline vehicles. This small change is primarily because of A/C correction factor, because MicroFacPM currently does not account for direct speed correction factor for gasoline vehicles. The maximum estimated emission rates for the diesel vehicles and the average fleet are calculated as 581 mg/mi and 21 mg/mi, respectively, at 10 mph, whereas the minimum estimated emission rates are calculated as 317 mg/mi and 13 mg/mi, respectively, for speeds >50 mph. Therefore, speed is a very sensitive variable in the calculation of emission rates for diesel heavy-duty vehicles.

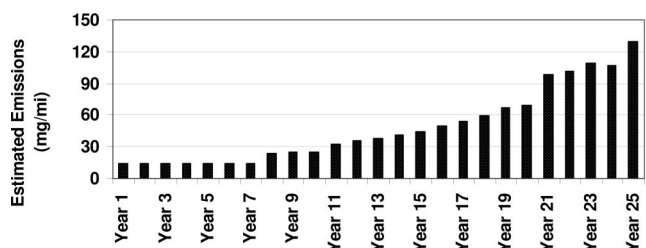
Figure 4b presents the effect of speed for heavy-duty diesel vehicles. Heavy-duty diesel vehicle classes 2B to 5 are represented by light, classes 6 and 7 by medium, and classes 8A and 8B by heavy heavy-duty diesel vehicles. In comparison to speed 10 mph, estimated emission rates at 50 mph are dropped by ~54%, 46%, and 43% for light, medium, and heavy heavy-duty diesel vehicles, respectively. Much of the emission rate reduction occurs by attaining a speed of 25 mph, where emissions are reduced



(a) Gasoline vehicles



(b) Diesel vehicles



(c) Yearwise fleet

Figure 3. Estimated PM_{2.5} emission rate distribution for (a) gasoline vehicle fleet, (b) diesel vehicle fleet, (c) year-wise vehicle fleet (all diesel and gasoline vehicles).

by ~40%, 32%, and 29% for light, medium, and heavy heavy-duty diesel vehicles, respectively.

Ambient Temperature

Ambient temperature is used to calculate cold engine correction and A/C correction factors (Figure 1b). In MicroFacPM, the effect of both the cold engine correction and the A/C is applied for LDGVs and trucks (<8500 lb) only.

Figure 5 presents the effect of A/C correction factors at different ambient temperatures. In this case, it is assumed that all of the vehicles are running in the hot stabilized mode, that is, no correction for cold engine starts. The estimated emission rates for LDGVs and trucks (<8500 lb) and for the composite vehicle fleet are increased by 17% and 6%, respectively, at 100 °F compared with ambient temperatures <65 °F.

A cold engine start or engine operating under transient conditions has a significant effect on estimated PM emission rates, which depends on the ambient temperature and length of trip. The cold mileage percentage for LDGVs and trucks (<8500 lb) after a 1-mi trip is estimated to be ~68% at 20 °F and decreases with the increase in temperature (Figure 6). At 90 °F, estimated cold mileage percentage is ~32%. The cold running emission rate is multiplied by the cold mileage percentage to obtain the fraction of distance traveled with cold engine. There is no effect on estimated emissions of cold start after a vehicle travels 8.5 mi.

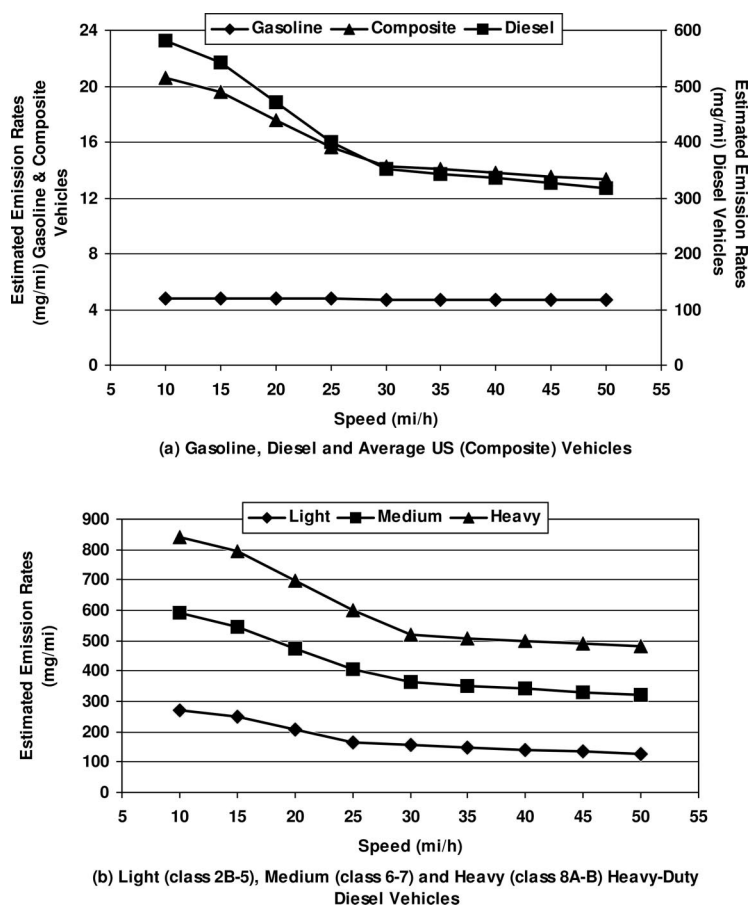


Figure 4. Variation in PM_{2.5} estimated emission rates because of speed for average U.S. vehicle fleet: (a) gasoline, diesel, and composite and (b) class.

We recommend using the length of trip for the vehicle on the site-specific basis. In the absence of site-specific information default length of trips for LDGVs and trucks⁶ (e.g., default length of trips used in MOBILE6 for a new car is 8.46 mi and for a 25-yr-old car is 3.32 mi) is used in MicroFacPM. Figure 7 shows the combined effect of cold mileage and A/C effects with the change in ambient temperature. This shows an increase in estimated emission rates approximately by 33% at 20 °F, 28% at 40 °F, 23% at

60 °F, and 18% at 80 °F. The increase in emissions at high temperatures is because of the A/C correction factor and the cold engine correction factor, whereas at low temperatures the increase is because of the cold engine correction factor. The model's output for heavy-duty vehicles and diesel vehicles is not as sensitive to temperature effects, because no A/C or cold engine correction factor is applied for diesel vehicles. In the absence of any specific information for cold engine correction factor and A/C

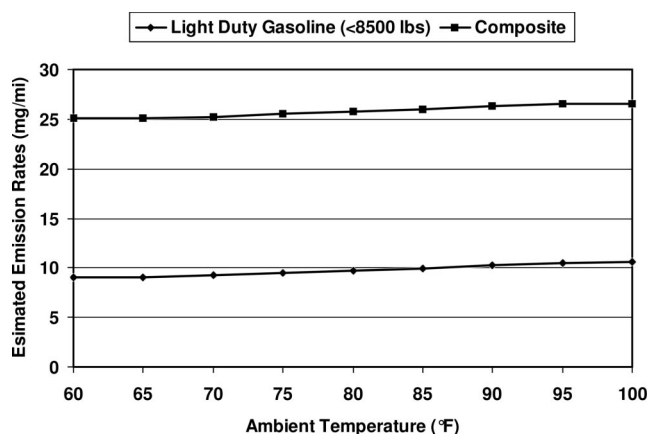


Figure 5. Effect of ambient temperature on PM_{2.5} estimated emission rates because of A/C use for average U.S. LDGV and LDGT (<8500 lb) fleet.

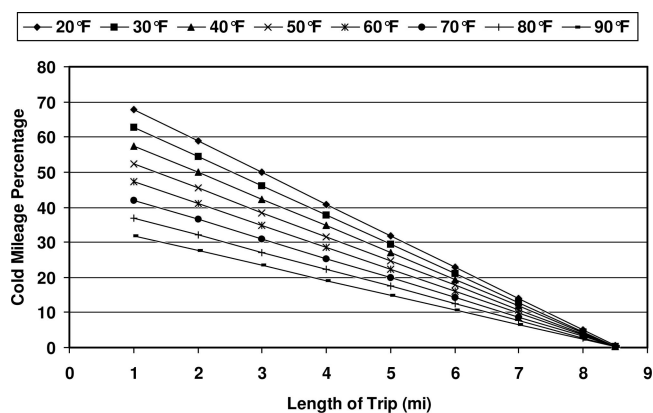


Figure 6. Effect of length of trip on cold mileage percentage because of ambient temperature for average U.S. LDGV and LDGT (<8500 lb) fleet.

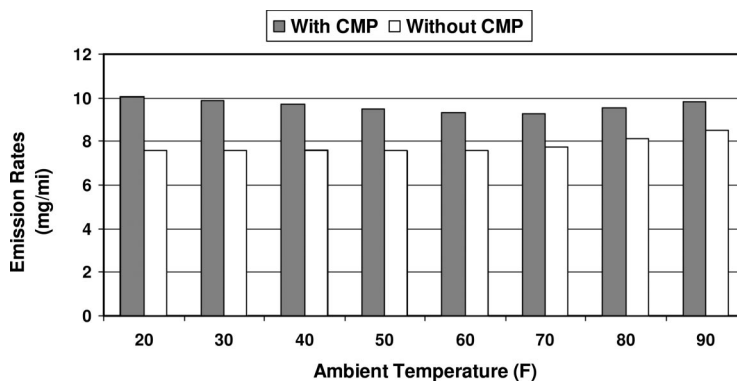


Figure 7. Effect of ambient temperature because of the cold engine correction and A/C factor for average U.S. LDGV and LDGT (<8500 lb) fleet.

factor for heavy-duty and diesel vehicles, MicroFacPM does not account for these corrections.

RH

RH, together with ambient temperature, is used to calculate the apparent temperature. MicroFacPM calculates apparent temperature from the methodology developed by Meisner and Graves.⁷ The demand factor for A/C use is calculated from the apparent temperature and the time of day. The default value for morning/afternoon is 6:00 a.m. to 10:00 a.m. and 4:00 p.m. to 9:00 p.m. Peak sun (solar load) is from 10:00 a.m. to 4:00 p.m., and night is between 6:00 p.m. and 6:00 a.m. The malfunction rate (non-functional A/C) of A/C systems is accounted in the calculated A/C demand for the vehicles depending on the vehicle age per MOBILE6 recommendation.⁸ Similar to MOBILE6, MicroFacPM has no A/C correction for apparent temperatures <65 °F. In addition, apparent temperatures >95 °F trigger an assumption of full A/C use. RH is not a sensitive input parameter in the calculation of composite fleet average emission rates. At 75 °F, estimated emission rates for LDGVs and trucks (<8500 lb) increase by only 2% and for the composite vehicle fleet increases by only 1% for a RH increase of 70% (from 30% to 100%).

Percentage of High-Emitting Vehicles

MicroFacPM requires site-specific information on “smoking” vehicles to account for the high-emitting vehicles, which can be determined by roadside surveys in a local area. Smoking or high-emitting vehicles are defined as those vehicles emitting particulate emissions above the emission standard set by EPA. This percentage can be estimated by remote sensing studies or on-road survey. Estimated high-emitter $PM_{2.5}$ emission rates for light-duty vehicles and trucks (<8500 lb), heavy-duty vehicles (>8500 lb), and the composite vehicle fleet are displayed in Figure 8. Estimated $PM_{2.5}$ emission rates for the 1990, 1995, 2000, 2005, and 2010 average U.S. light-duty vehicle fleet are increased by a factor of ~2.3, 2.9, 3.7, 5, and 5.7, respectively, with an increase of 5% in the smoking vehicle fleet (compared with 0%; Figure 8a). However, only a very small increase in the estimated $PM_{2.5}$ emission rates (39–51%) is noticed with a 5% increase of nonnormal emitters considering the heavy-duty U.S. vehicle fleet

(Figure 8b). As discussed in the companion paper¹ (Emission Rates section), in the absence of any specific information on the nonnormal emission rates for heavy-duty diesel vehicles (>8500 lb), this analysis is performed assuming emission rates for nonnormal heavy-duty diesel vehicles (>8500 lb) as 10 times of those from the equivalent normal emitting vehicles. Estimated fine particulate matter ($PM_{2.5}$) emission rates for the current average U.S. vehicle fleet increased by a factor of ~1.7, 1.9, 2.1, 2.5, and 2.8 for the 1990, 1995, 2000, 2005, and 2010 fleet, respectively (Figure 8c). This change in estimated emission rates is because of change in PM emission standards over time as newer vehicles have improved pollution control and fuel technology compared with older vehicles. Currently, the model does not account for the future technology vehicles and emission standards.

Additional Features of MicroFacPM

The MicroFacPM approach to calculate composite emission rates is based on disaggregated inputs; therefore, we can also calculate the contribution of PM emissions from different vehicle classes separately. Contribution to $PM_{2.5}$ exhaust emissions per vehicle types is shown in Figure 9. Approximately 20% of exhaust $PM_{2.5}$ emissions result from LDGV (63% of fleet); 7% from light-duty diesel vehicle (LDDV; 0.5% fleet); 12% from light-duty gas truck (LDGT; 30% of fleet; 9% from LDGT12 and 3% from LDGT34); 3% from light-duty diesel truck (LDDT; 0.2% of fleet; 2% from LDDT12 and 1% from LDDT34); 2% from heavy-duty gas vehicle (HDGV) and heavy-duty gasoline buses (HDGB) (3.5% of fleet; 2 from HDGV and <0.1% from HDGB); 9% from light heavy-duty diesel vehicles (HDDV2B5; 1% of fleet; 5% from HDDV2B; 2% from HDDV3, 1% from HDDV4, and 0.5% from HDDV5); 11% from medium heavy-duty diesel vehicles (HDDV67; 0.6% of fleet; 4% from HDDV6 and 7% from HDDV7); 31% from heavy heavy-duty diesel vehicles (HDDV8; 1% of fleet; 8% from HDDV8A and 23% from HDDV8B); and 5% from heavy-duty diesel buses (0.2% of fleet; 1% from HDDTB and 4% from heavy-duty diesel school buses).

Contribution to the estimated $PM_{2.5}$ exhaust emissions as a function of the age of the vehicle fleet is presented in Figure 10. The vehicles ≤10 yr old constitute ~66% of the fleet but contribute only 38% of the total

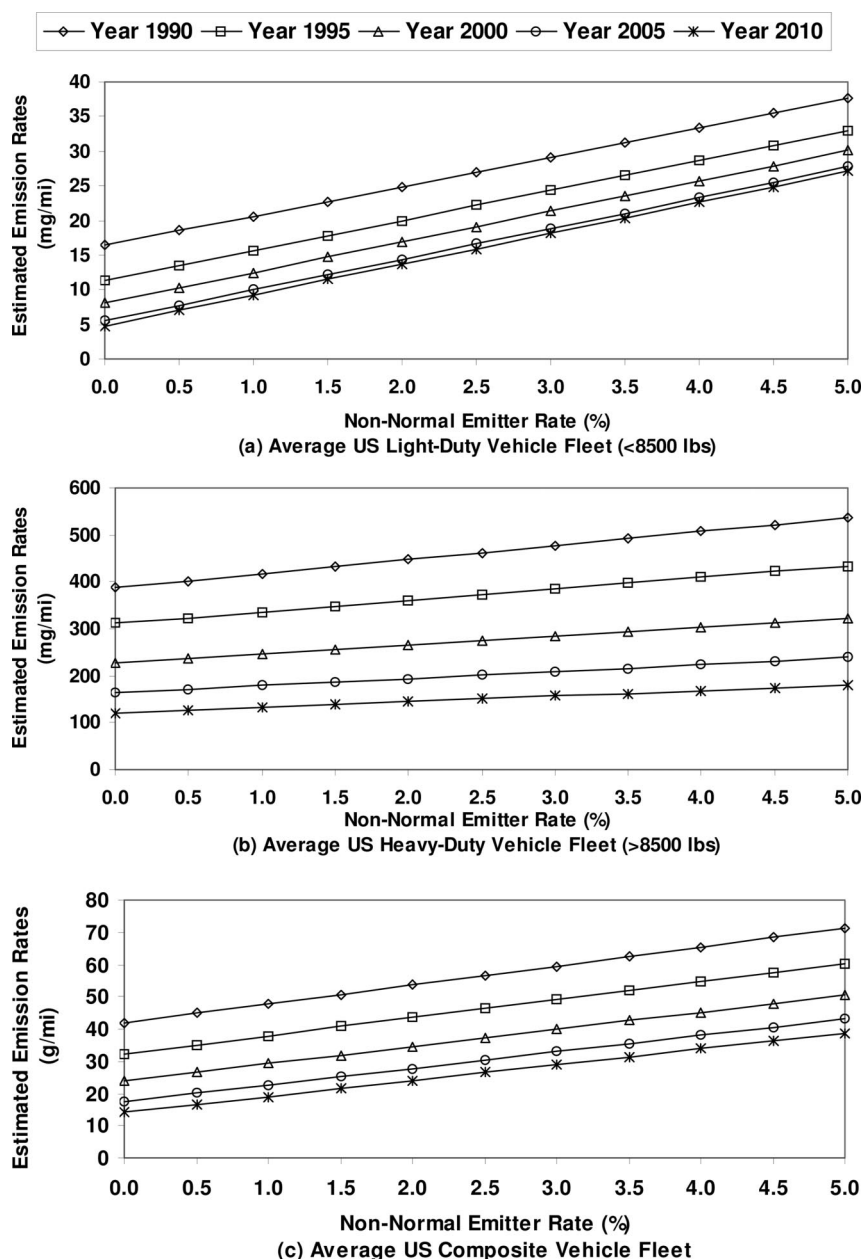


Figure 8. Effect of nonnormal emitting vehicles on estimated exhaust $PM_{2.5}$ emission rates: (a) light-duty, (b) heavy-duty, and (c) composite.

exhaust $PM_{2.5}$ emissions, whereas vehicles >20 yr old (5% of the fleet) contribute ~20% of total exhaust $PM_{2.5}$ emissions. Vehicles >15 yr compose ~13% of the fleet and contribute 36% of the total exhaust $PM_{2.5}$ emissions.

The comparison of estimated emissions per modeled source (gasoline, diesel, tire, and brake wear) is shown in Figure 11. The most significant $PM_{2.5}$ contribution is from tailpipe exhaust of diesel-powered vehicles (58%), followed by tailpipe exhaust of gasoline-powered vehicles (30%). Note that gasoline vehicles are ~97% of the total fleet as compared with 3% for diesel vehicles. The combined contributions from brake wear and tire wear is ~12% (~6% from each). However, emission rates will largely depend on the composition of traffic fleet, age, and location. Default traffic fleet results shown in Figure 11 will be very different compared with runs at different

times in urban areas consisting mostly of light-duty vehicles with cold engines. For example, assuming 98% light-duty vehicles during a 1-mi trip at 50 °F at an average speed of 30 mph will result in a >80% contribution from gasoline-fueled vehicles.

Emission estimates for MicroFacPM are compared with real-world emission factors in different fleet years. Figure 12 illustrates an example of the change in estimated $PM_{2.5}$ emission factors for different fleet years with a fixed vehicle fleet composition, assuming that there are no smoking vehicles in the fleet. The composite fleet average emission factor estimate for 2010 is approximately one-third the estimated emission factor in 1990 and approximately half the estimated emission factor in 2000. These estimates are made with the assumption that there is no change in vehicle pollution control and fuel

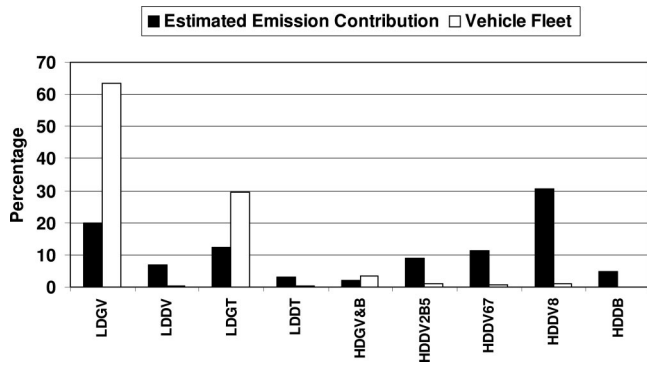


Figure 9. Contribution to estimated exhaust PM_{2.5} emissions per vehicle type.

technology, and changes are because of the replacement of older vehicles with newer ones.

RESULTS

Fleet emission models are difficult to evaluate on their own in real-world applications. The best way to evaluate emission models is either by confining the emissions in a tunnel or use in conjunction with dispersion models, although those have their own uncertainties.⁹ MicroFacPM was evaluated using tunnel study data from the Tuscarora Mountain Tunnel in 1999.^{10,11} Additional evaluation is also presented using data from the Sepulveda Tunnel and Van Nuys Tunnel conducted in 1995.¹² The methodology to calculate emission rates in tunnels, experimental descriptions, and particulate matter (PM) emission rates are explained in detail by Gertler et al.^{10,12} The emission factors in tunnels (grams per mile) are determined by knowing the passage of dilution air through the tunnel and the concentrations in the entrance and exit channels. The emission rate of all of the vehicles in the tunnel for a given species M is as follows:

$$M = \sum C_{out} V_{out} - \sum C_{in} V_{in} \quad (2)$$

where C_{out} , C_{in} , V_{out} , and V_{in} are observed concentration at the tunnel outlets, observed concentration at the tunnel inlets, volumetric airflow out at the tunnels, and volumetric airflow in at the tunnels, respectively.

In these cases, the tunnel was operating without fans, and $V_{out} = V_{in}$. If N is the number of vehicles that went

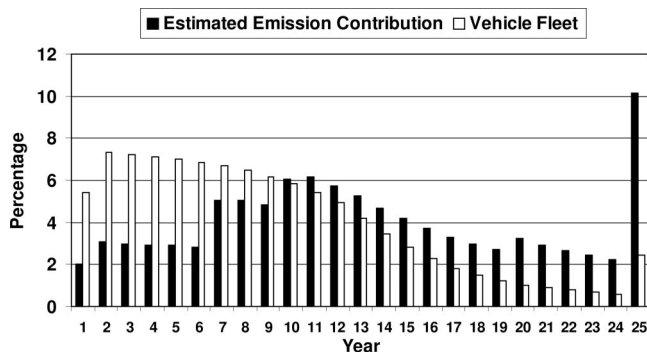


Figure 10. Contribution to estimated exhaust PM_{2.5} emissions per age of vehicle fleet.

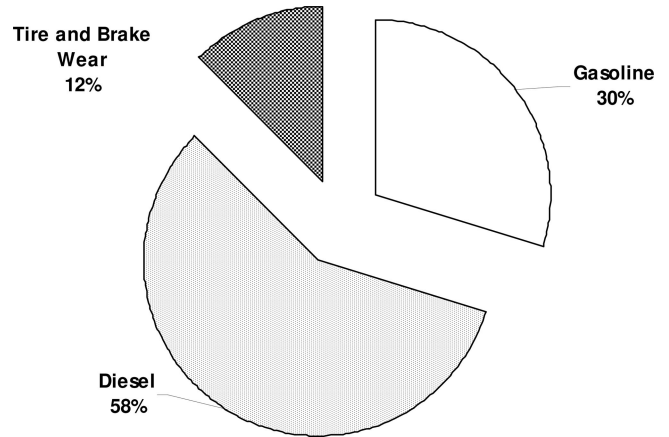


Figure 11. Contribution to estimated PM_{2.5} emissions per modeled sources for the U.S. vehicle composition shown in Figure 2 (gasoline, diesel, tire and brake wear).

through the tunnel length L during sampling period, then emission factor EF is as follows:

$$EF = M/(NL) \quad (3)$$

The presentations of data in the figures below are presented to demonstrate strong qualitative support as discussed in the text for application of MicroFacPM. The quantity of available measurement data was considered to be insufficient for a more detailed statistical analysis in the text.

Tuscarora Mountain Tunnel

The Tuscarora Mountain Tunnel is located along Interstate 76, also called the Pennsylvania Turnpike, running east-west through the Tuscarora Mountain in South Central Pennsylvania. It is a two-bore tunnel, two lanes per bore, and 1.01 mi long. The tunnel is flat (grades +0.3% toward the middle from the either end) and straight. The ventilation system in the tunnel was not operated during the experiment, and the tunnel was ventilated entirely by the traffic piston effect and the prevailing westerly wind. Because no injection of fresh air occurred and no material

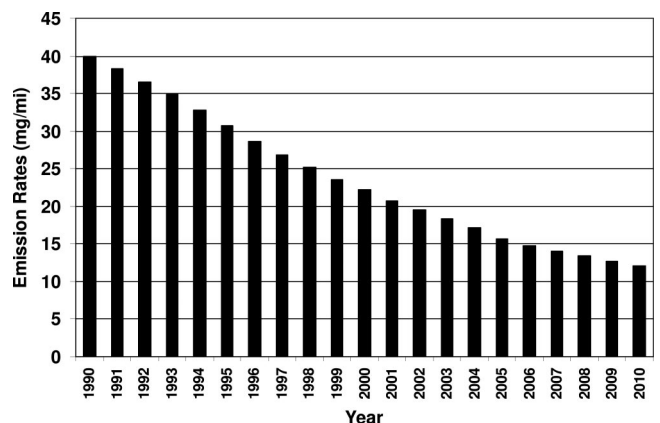


Figure 12. Average U.S. vehicle (composite) fleet emission rates for exhaust PM_{2.5} between 1990 and 2010.

Table 2. Tuscarora Mountain Tunnel study during evaluation time.

Start Time	Flow (No.)	Speed (mph)	LD (%)	HDGV (%)	HDDV4 (%)	HDDV5 (%)	HDDV6 (%)	HDDV7 (%)	HDDV8 (%)	Observed PM ₁₀ (mg/mi)	Observed PM _{2.5} (mg/mi)
12:00 a.m.	532	54.9	62.78	0.94	0.94	1.32	1.13	5.45	27.44	—	99
8:00 p.m.	385	54.8	45.97	1.04	0.26	1.04	1.56	3.90	46.23	113	210
10:00 p.m.	293	57.0	35.49	0.68	0.34	1.02	1.71	8.53	52.22	—	140
12:00 a.m.	205	54.9	15.12	0.00	1.95	0.00	0.98	17.56	64.39	138	—
2:00 a.m.	190	55.1	13.68	0.00	1.05	3.16	1.58	20.53	60.00	183	260
7:00 p.m.	452	57.7	53.10	0.88	0.44	0.44	1.33	8.41	35.40	82	111
9:00 p.m.	357	54.4	41.46	0.84	0.84	0.56	3.36	11.76	41.18	—	102
11:00 p.m.	249	53.6	28.11	1.61	0.40	0.00	0.40	9.24	60.24	126	120
1:00 a.m.	201	55.0	21.39	1.00	0.50	1.49	0.50	10.95	64.18	—	104
4:00 p.m.	726	53.2	69.56	0.96	0.14	0.96	0.41	2.62	25.34	—	105
5:00 a.m.	247	58.1	35.63	0.00	1.62	0.81	2.43	15.38	44.13	102	166
7:00 a.m.	404	57.5	51.49	0.50	0.25	1.73	2.72	6.19	37.13	—	—
9:00 a.m.	574	53.8	63.76	0.87	0.52	0.70	1.05	6.97	26.13	82	27
5:00 p.m.	814	56.9	86.73	0.49	0.37	0.61	0.61	2.83	8.35	34	77
11:00 a.m.	553	57.0	88.61	0.18	0.54	0.90	0.18	3.25	6.33	—	133
1:00 p.m.	536	56.5	82.84	1.49	0.00	0.93	0.37	4.29	10.07	—	34
3:00 p.m.	489	57.0	83.03	0.41	0.41	1.64	0.20	2.25	12.07	—	25
5:00 p.m.	440	59.5	85.68	0.68	0.91	0.91	0.23	2.05	9.55	31	12
10:00 a.m.	530	58.1	82.08	0.00	0.57	1.13	0.38	5.09	10.75	13	45
12:00 a.m.	1678	61.7	83.19	0.42	0.42	0.77	0.36	2.56	12.28	42	31

was removed, the situation was suitable for the calculation of PM emission rates. Samplers were located a few feet in from each portal in the exhaust vents above the roadway and anemometers on the walkways adjacent to the road. Studies were conducted between May 18 and 22, 1999. All of the experimental runs were of 1-hr duration except the last, which was 2 hr in duration. Average vehicle speed was determined by radar gun. The detailed traffic fleet was determined on run-by-run basis.

Coarse PM (PM₁₀) measurements were performed using the DustTrak 8520 Aerosol Monitor (TSI, Inc.), which is a portable, battery-operated laser-photometer that uses light scatter technology to determine real-time mass concentration. It is reported that the traditional method of collecting particulate samples on filters is prone to error in short-duration field studies because of the small size of samples,^{13,14} and these instruments perform better than traditional filter measurements.^{15,16}

PM_{2.5} mass measurements were performed using IMPROVE (Interagency Monitoring of Protected Visual Environments) samplers.¹⁷ The standard IMPROVE sampler has four modules, each consisting of a size-selective inlet for PM₁₀, a cyclone to provide a PM_{2.5} particle size cutoff based on the flow rate, collection substrates, a critical orifice that provides the proper flow rate for the desired particle size cutoff, and a vacuum that produces the flow.¹⁰ In this study, the PM₁₀ module of IMPROVE sampler was not used.

Table 2 summarizes the traffic fleet data and speeds for 20 runs during the study period. The speeds varied from 53.2 to 61.7 mph, and light-duty vehicles (<8500 lb) comprised from 13.7 to 88.6%. The minimum trip length before reaching the tunnel was estimated as 15 min, and trips >50 min before reaching the tunnel constitute some 75% of all of the trips.¹⁰ Therefore, vehicles were operating mostly in the hot-stabilized mode. In North America,

passenger vehicles mostly consist of gasoline-power engines; therefore, all of the light-duty vehicles (<8500 lb) were assumed to be gasoline powered. The age distributions of the fleet per vehicle type for each run were known for the most part. The light-duty fleet consisted mostly new vehicles, constituting ~64% tier 1 (1994+) vehicles (ranged from 50% to 68.8%), 35% tier 0 (1981–1993) vehicles (ranged from 29.6% to 48.1%), and 1% pre-1981 vehicles (ranged from 0% to 3.2%). For the distribution of LDGV and LDGT, we assumed the national default values, that is, 66% vehicles are LDGV and 34% are LDGT. Because the fleet was dominated by mainly heavy heavy-duty diesel vehicles and tier 1 light duty vehicles and trucks (<8500 lb), the precise split of LDGV and LDGT is not needed.

The yearly age distributions were available for heavy-duty vehicles except classes 7 and 8, which were grouped into 1993+, 1991–1993, 1991, and pre-1990 (1985). In the absence of precise split between class 8A and class 8B vehicles, we assumed national average for the breakdown of class 8A and 8B vehicles, that is, 30% class 8A vehicles and 69% class 8B vehicles. The age distribution for vehicles classes 7 and 8 was grouped into 1993+, 1991–1993, 1991, and pre-1990 (1985). The heavy-duty vehicles age-wise distribution for runs 4 and 5 (May 19, Wednesday; start time: 12:00 a.m. and 2:00 a.m.) could not be found; therefore, we assumed age distribution for these runs similar to run 9 (May 20, Thursday; start time: 1:00 a.m.).

In this study, major input variables needed to run MicroFacPM were available, except for the percentage of smoking vehicles. The Tuscarora Tunnel fleet is younger than the average fleet, consisting mainly of well-functioning vehicles. As discussed in the companion paper, some high emitters are found in nearly every model year, but the highest tailpipe emissions from vehicles with an ~10-yr-old MicroFacPM default value for smoking (i.e. high

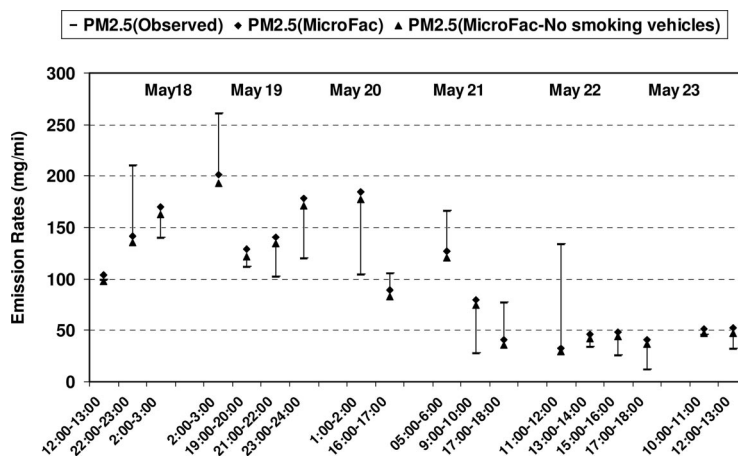


Figure 13. Comparison between the observed and MicroFacPM estimated $PM_{2.5}$ emission rates for the Tuscarora Mountain Tunnel between May 18 and 23, 1999.

emitting) vehicles depends on the average age of the fleet starting with 0.1%/yr (e.g., for 10-yr-old fleet as 1% and for 15-yr-old fleet as 1.5%). In this case, the default value for smoking vehicles will be used as 0.4%, because the fleet was ~4 yr old. Additionally, model results are also presented, assuming no smoking vehicles in the fleet. In view of the large percentage of diesel heavy-duty vehicles classes 7 and 8 (HDDV7, HDDV8A, and HDDV8B) and because vehicles were operating in the hot-stabilized modes, MicroFacPM results will not be very sensitive to ambient temperature changes. Tuscarora Mountain Tunnel is relatively flat, located on an interstate highway; therefore, brake wear emissions are not considered. Measurements showed that $PM_{2.5}$ data for runs 4 and 5 were highly suspect and, therefore, are not included in the study.¹⁰ PM_{10} emission factors estimates were obtained for 11 runs, that is, runs 2, 4, 5, 6, 8, 11, 13, 14, 18, 19, and 20. Figures 13 and 14 compare the observed and MicroFacPM emission rates for $PM_{2.5}$ and PM_{10} , respectively. Note that the modeled emission factors do not include the re-entrained road dust. In general, the performance of MicroFacPM is very encouraging. The average observed and MicroFacPM values for $PM_{2.5}$ (18 runs) are 100 and 103 mg/mi, respectively, and for PM_{10} (11 runs) are 141 and 129 mg/mi, respectively. The average contributions

(average of 18 runs) of $PM_{2.5}$ emission factors are as follows: 2.4% from 58.7% LDGV and LDGT, 2.9% from 0.4% LDDV and LDDT, 0.04% from 0.8% HDGV, 3.6% from 1.5% HDDV45, 1.1% from 0.9% HDDV6, 14.7% from 6.5% HDDV7, 20% from 9.4% HDDV8A, 51.6% from 21.8% HDDV8B, and 3.7% from tire wear emissions. The contribution of $PM_{2.5}$ emissions ranged from 0.2% (run 4) to 6.5% (run 13) for LDGV and LDGT, 0.2% (run 4) to 8.3% (run 13) for LDDV and LDDT, 0% (run 10) to 0.2% (run 13) for HDGV, 0% (run 7) to 9% (run 15) for HDDV45, 0.2% (run 7) to 3.7% (run 6) for HDDV6, 6.6% (run 2) to 28.6% (run 17) for HDDV7, 13.4% (run 13) to 24.2% (run 7) for HDDV8A, 33.2% (run 13) to 63.2% (run 7) for HDDV8B, and 1.9% (run 4) to 7.5% (run 13) for tire wear.

Sepulveda Tunnel

The Sepulveda Boulevard Tunnel is under the Los Angeles International Airport (LAX) in Los Angeles, CA. It is a covered roadway (covered portion: 0.36 mi long), straight, and approximately flat in the covered portion. The top portion is part of the airplane runway and taxiway for LAX. There are two bores (three lanes each) separated by a concrete wall running most of the length of the tunnel with a sidewalk on the right of the each bore.

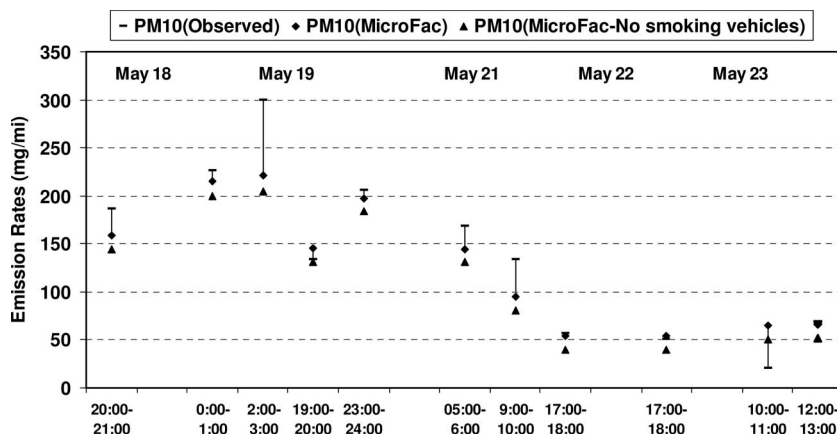


Figure 14. Comparison between the observed and MicroFacPM estimated PM_{10} emission rates for the Tuscarora Mountain Tunnel between May 18 and 23, 1999.

Table 3. Sepulveda Tunnel study during evaluation time.

Run No.	Start Time	Ambient Temp (°F)	Flow (No.)	Speed (mph)	LD (%)	Observed PM ₁₀ (mg/mi)	Observed PM _{2.5} (mg/mi)
Tuesday 10/03/1995							
1	7:00	66.9	2650	47.5	97.96	33	—
2	9:00	78.1	1998	47.7	96.85	48	47
3	12:00	80.1	2908	44.2	98.11	47	46
4	15:00	77.0	3371	44.4	98.01	32	41

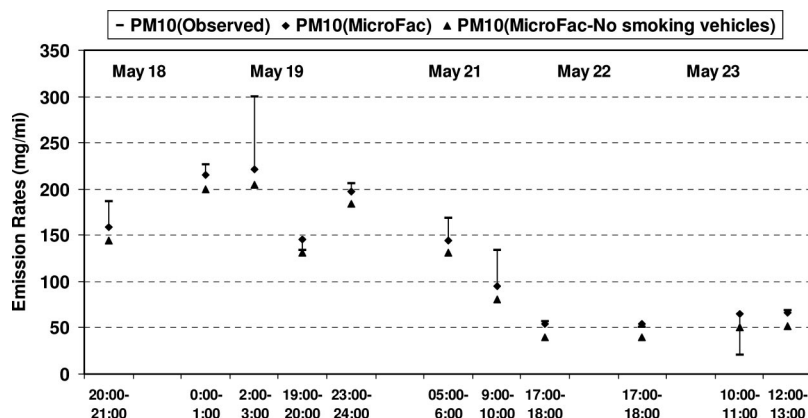
The experiment was conducted in the west bore, with the ventilation system sealed off, on October 3, 1995. The west bore carries Sepulveda Boulevard southbound from the LAX terminals. Following the tunnel, there is a turn lane to allow access to the on ramps to Highway 105, which also connects to 405. The vehicles going through the tunnel head toward these freeways, and in some time periods these vehicles do occasionally back up into the tunnel. The fleet was reported to be urban and running in hot-stabilized mode.¹²

PM₁₀ and PM_{2.5} samplers were located inside the tunnel on the sidewalks. Desert Research Institute medium-volume PM₁₀ and PM_{2.5} samplers were used to collect four samples of PM₁₀ and three samples of PM_{2.5} for 1-hr duration.¹² The mass emission factors were determined from the actual filter mass collected. The run descriptions during the study period are presented in Table 3. The speeds, ambient temperatures, and light-duty vehicle (<8500 lb) percentage varied from 44.2 to 47.7 mph, from 66.9 °F to 80.1 °F, and from 96.9% to 98.1%, respectively. The re-entrained road dust was estimated to be $\sim 11.7\% \pm 5.4\%$ for PM₁₀ and $11.5\% \pm 4.1\%$ for PM_{2.5} of the observed emission factors. The vehicle fleet was separated into light-duty vehicles (<8500 lb) and heavy-duty vehicles (>8500 lb). The light-duty fleet consisted of mostly tier 0 (1981–1993) vehicles constituting $\sim 78.9\%$ (ranged from 76.2–80.7%); tier 1 (1994+) and pre-1981 vehicles were $\sim 5.6\%$ (ranged from 4–7.7%) and 15.5% (ranged from 11.6–17.2%), respectively. In the absence of any specific information on heavy-duty fleet composition, we used national default values^{2,3} for detailed vehicle class distribution and the age-wise distribution of heavy-duty vehicle (>8500 lb). As observed, the overall average age of

the fleet was 1985.9; therefore, MicroFacPM was run assuming 1% of high-emitting vehicles in the fleet. In addition, for the comparison purpose, we also ran the model assuming no smoking vehicles in the fleet. The observed and MicroFacPM emission factors for PM_{2.5} and PM₁₀ are shown in Figures 15 and 16, respectively. MicroFacPM estimated emission factors do not include re-entrained road dust. The average observed and MicroFacPM values (assuming 1% high emitters in the fleet) for PM_{2.5} (three runs) are 45 and 23 mg/mi, respectively, and for PM₁₀ (four runs) are 40 and 36 mg/mi, respectively. The modeled PM₁₀ emission factors are high compared with PM_{2.5} because of the presence of tire and brake wear emissions, which mostly have particles $>2.5 \mu\text{m}$ in size. MicroFacPM uses tire and brake wear emission rates as used in PARTS, that is, 2 mg/mi (PM₁₀) and 0.5 mg/mi (PM_{2.5}) for tire wear, and 7.84 mg/mi (PM₁₀) and 2.05 mg/mi (PM_{2.5}) for brake wear. Therefore, the difference between the observed and model estimates for PM_{2.5} is larger than for PM₁₀. This could indicate the presence of more heavy-duty diesel vehicles than the default values, the presence of some smoking vehicles in the fleet, and possibly over-estimated brake/tire wear emission rates for PM₁₀. Because of the limited number of measurements at this tunnel, it is not possible to understand the poor agreement between the modeled and observed values, especially for PM_{2.5}. These issues will be further investigated with the availability of new data.

Van Nuys Tunnel

The Van Nuys Tunnel is under the runway of Van Nuys Airport in Van Nuys, CA. There are two bores (three lanes

**Figure 15.** Comparison between the observed and MicroFacPM estimated PM_{2.5} emission rates for the Sepulveda Tunnel on October 3, 1995.

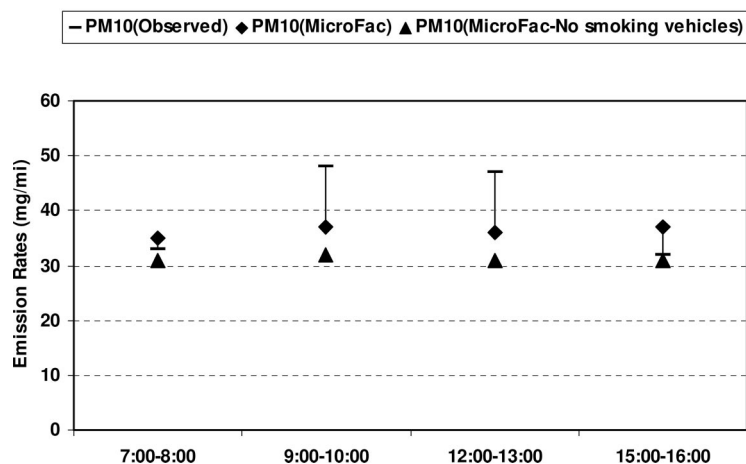


Figure 16. Comparison between the observed and MicroFacPM estimated PM_{10} emission factors for the Sepulveda Tunnel on October 3, 1995.

each) 0.14 mi long with a narrow sidewalk adjacent to the north and south lanes. This tunnel is straight, and grade varies from -1.7% to 1% . The experiment was conducted in the north bore, with ventilation system closed, from June 9–12, 1995. The traffic signals are located a few meters away at the entrance and exit of the tunnel, which often results in acceleration of the vehicles at the entrance and deceleration at the exit. The fleet was reported to be running in the hot-stabilized mode.¹²

PM_{10} samplers, similar to those used in the Sepulveda Tunnel, were located in the north bore. In some cases, because of low filter loadings, results from the gravimetric measurements were highly unreasonable, that is, filter masses were lower after particulate loading. For runs (1, 3, 4, and 9) where full chemical speciation and loadings were sufficient, the mass emission factors were determined from the sum of species. The run descriptions during the study period are presented in Table 4. The speeds, ambient temperatures, and light-duty vehicle (<8500 lb) percentage varied from 42.4 to 45.4 mph, from 84.2°F to 108.9°F , and from 95.6% to 99.4%, respectively. The re-entrained road dust was estimated to be $\sim 20.9\% \pm 7.4\%$ of the observed emission factors. The vehicle fleet was separated into light-duty vehicles

(<8500 lb) and heavy-duty vehicles (>8500 lb). The light-duty fleet consisted of mostly tier 0 (1981–1993) vehicles constituting $\sim 71.1\%$ (ranged from 63.9 to 75.4%); tier 1 (1994+) and pre-1981 vehicles were $\sim 2\%$ (ranged from 0.9% to 3%) and 26.9% (ranged from 23.7 to 31.2%), respectively. In comparison to Sepulveda Tunnel, the average light-duty vehicle fleet was older by 2 yr in this tunnel. In the absence of any specific information on heavy-duty fleet, we used national default values^{2,3} for detailed vehicle class distribution and the age-wise distribution of the heavy-duty vehicle (>8500 lb). As observed, overall average age of the fleet is older than the Sepulveda by ~ 2 yr; therefore, MicroFacPM was run assuming 1.2% of high-emitting vehicles in the fleet. In addition, we also ran the model assuming no smoking vehicles in the fleet. The observed and MicroFacPM emission factors for PM_{10} are shown in Figure 17. The average observed and MicroFacPM values for PM_{10} (9 runs) are 67 and 41 mg/mi, respectively. Runs 2 and 9 have very high observed values. No remote sensing study was carried out to understand the reason for these high values. The probable reason may be the presence of a small number of smoking vehicles and/or the fleet may be dominated by older heavy-duty diesel vehicles (HDDV8). If we exclude runs 2 and 9,

Table 4. Van Nuys Tunnel study during evaluation time.

Run No.	Start Time	Ambient Temp ($^\circ\text{F}$)	Flow (No.)	Speed (mph)	LD (%)	Observed PM_{10} (mg/mi)	Observed $PM_{2.5}$ (mg/mi)
Friday, June 9, 1995							
1	7:00	86.2	1558	42.6	95.57	39	—
2	10:00	90.1	1624	42.4	96.00	173	—
3	18:00	84.2	1554	43.3	98.46	52	—
Saturday, June 10, 1995							
4	11:00	102.0	1603	44.7	98.63	56	—
5	21:00	88.3	670	43.4	99.25	57	—
Sunday, June 11, 1995							
6	19:00	98.8	1046	45.4	99.43	29	—
Monday, June 12, 1995							
7	7:30	94.6	2183	43.2	95.83	31	—
8	12:00	107.8	2021	43.6	97.62	115	—
9	15:00	108.9	1315	44.2	95.74	51	—

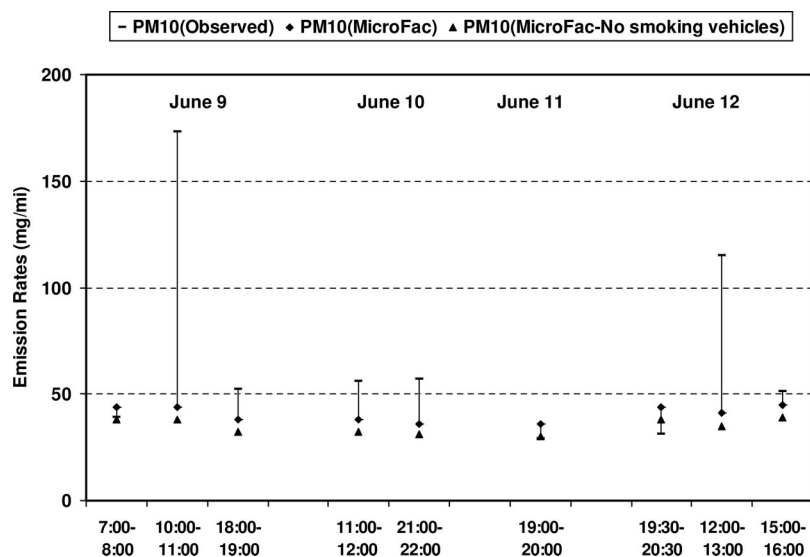


Figure 17. Comparison between the observed and MicroFacPM estimated PM_{10} emission rates for the Van Nuys Tunnel between June 9 and 12, 1995.

then average observed and MicroFacPM values for PM_{10} (7 runs) are 45 and 40 mg/mi, respectively. Note that MicroFacPM estimated emission factors do not include re-entrained road dust, which is ~21% of the observed emission factors. As discussed in the companion paper,¹ the methodology for re-entrained road dust needs revision; the current version of MicroFacPM, therefore, does not account for re-entrained road dust. However, if needed, the re-entrained road dust emission rates and methodology in MicroFacPM may be used in a similar manner to that in the Particulate Matter Emission Factor model.⁹

DISCUSSION

A microscale emission factor model for predicting real-world real-time motor vehicle PM (MicroFacPM) emission has been developed. MicroFacPM requires a few input variables to characterize the local real-time fleet. The sensitivity analysis has shown that model results are very sensitive to vehicle fleet composition, speed, and percentage of high-emitting vehicles. The fleet compositions for each of the field studies evaluated in this paper were uniquely different from the national average used in the reported sensitivity study. Knowing the local fleet is a very critical factor in estimating local emissions. Vehicle class, fuel type, and vehicle age also categorize the fleet. For the present U.S. vehicle fleet, the $PM_{2.5}$ estimated emission rate decreases by a factor of ~0.64 for speeds >50 mph in comparison with a speed <10 mph. The changes in ambient temperature can influence estimated $PM_{2.5}$ emission rates for LDGVs and LDGTs (<8500 lb) ≤30%. The fleet $PM_{2.5}$ estimated emission rate in 2000 nearly doubled for a smoking vehicle fleet increase of 5% compared with 0%. The fleet estimated emission rate is more sensitive to smoking vehicles in the 2000s than in the 1990s. Estimated emission rates are not very sensitive to variations in RH. MicroFacPM calculates the contribution of PM emissions from different vehicle categories and sources. The model can also be used to compare the effect of real-world emission rates in past and future years. Approximately 66% of the modeled exhaust $PM_{2.5}$ emissions

are contributed by diesel-powered vehicles, which compose ~3.4% of the vehicle fleet. Vehicles ≤10 yr old compose ~66% of the fleet but contribute only 38% of the exhaust $PM_{2.5}$ emissions, whereas those vehicles >20 yr old compose only 5% of the fleet but contribute ~20% of all of the exhaust $PM_{2.5}$ emissions. The fleet average exhaust $PM_{2.5}$ emission rate estimated for 2010 is less than one-third of the estimated emission rate for 1990 if there is no change in vehicle pollution control and fuel technology, and changes are because of the replacement of older vehicle fleets with newer ones.

MicroFacPM was evaluated using data from contemporary tunnel studies in the United States at three locations: Tuscarora Mountain Tunnel on the Pennsylvania Turnpike, Sepulveda Tunnel in Los Angeles, and Van Nuys Tunnel in Van Nuys. In the Tuscarora Mountain Tunnel, average speed and light-duty vehicle (<8500 lb) percentages varied from 53.2 to 61.7 mph and from 13.7 to 88.6%, respectively. For this site, the detailed breakdown of the traffic fleet was known for all of the runs. The observed and calculated MicroFacPM emission factors varied from 12 to 260 mg/mi and 41 to 201 mg/mi, respectively for $PM_{2.5}$ and 21–300 mg/mi and 54–221 mg/mi, respectively, for PM_{10} . $PM_{2.5}$ and PM_{10} comparisons for 18 and 11 runs, respectively, showed very encouraging results of the model with average observed and calculated MicroFacPM emission factors of 100 and 103 mg/mi, respectively, for $PM_{2.5}$ and 141 and 129 mg/mi, respectively, for PM_{10} . In the Sepulveda Tunnel, average speed and light-duty vehicle (<8500 lb) percentages varied from 44.2 to 47.7 mph and from 96.9 to 98.1%, respectively. The agreement between modeled and observed $PM_{2.5}$ is much less when compared with PM_{10} . The observed and calculated MicroFacPM emission factors varied from 41 to 47 mg/mi and 18 to 25 mg/mi, respectively, for $PM_{2.5}$; and from 32 to 48 mg/mi and 35 to 37 mg/mi, respectively for PM_{10} . Average observed and calculated MicroFacPM emission factors were 40 and 36 mg/mi, respectively, for $PM_{2.5}$ and 45 and 20 mg/mi, respectively, for PM_{10} . In the Van Nuys Tunnel, an average speed and light-duty vehicle (<8500 lb) percentage varied from 42.4 to 45.4 mph and

from 95.6 to 99.4%, respectively. The observed and calculated MicroFacPM emission factors varied from 29 to 173 mg/mi and 36 to 45 mg/mi, respectively, for PM₁₀. Average observed and calculated MicroFacPM emission factors were 67 and 41 mg/mi, respectively. The modeled emission factors in the above studies do not include re-entrained road dust. In the Sepulveda and Van Nuys Tunnel studies, the fleet composition and age-wise distributions for heavy-duty vehicles (>8500 lb) were not known. We will further evaluate the model as newer tunnel study data become available. We will also be evaluating the MicroFacPM performance in roadway environments. Although tunnel studies offer more controllable environments and are well suited for evaluations of emission models, there are several issues related to the dispersion of pollutants that must be examined in open roadway environments. In general, when input variables are known in detail, the evaluation study has shown very encouraging results between measured and calculated PM emission factors. MicroFacPM emission estimations are suitable for modeling air quality and human exposure in microenvironments near roadways with free-flowing traffic.

ACKNOWLEDGMENTS

The authors are grateful to Alan Gertler of the Desert Research Institute for providing the report (Gertler, A.W.; Gillies, J.A.; Pierson, W.R.; Rogers, C.F.; Sagebiel, J.C.; Abu-Allaban, M.; Coulombe, W.; Tarnay, L.; Cahill T.A. *Ambient Sampling of Diesel Particulate Matter*, Draft Final Report; DRI: Reno, NV, 2000) and detailed information on the traffic fleet for the Tuscarora Tunnel.

Disclaimer. The research by Alan Huber presented here was performed in part under the Memorandum of Understanding between EPA and the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) under agreement number DW13921548. This work constitutes a contribution to the NOAA Air Quality Program. Although it has been reviewed by EPA and NOAA and approved for publication, it does not necessarily reflect their policies or views.

REFERENCES

1. Singh, R.B.; Huber, A.H.; Braddock, J.N. Development of a Microscale Emission Factor Model for Particulate Matter (MicroFacPM) for Predicting Real-Time Motor Vehicle Emissions; *J. Air & Waste Manage. Assoc.* **2003**, *53*, 1204-1217.
2. Jackson, T.R. *Fleet Characterization Data for MOBILE6: Development and Distribution of Age Distributions, Average Annual Mileage Accumulation Rates, and Projected Vehicle Counts for Use in MOBILE6*, U.S. Environmental Protection Agency, Office of Mobile Sources, EPA420-R-01-047, MOBILE6 Document Number M6.FLT. 007; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 2001.
3. Browning, L.; Chan, M.; Coleman, D.; Pera, C. *Update of Fleet Characterization Data for Use in MOBILE6—Final Report*, EPA420-P-98-016, MOBILE6 Document Number M6.FLT. 002; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 1998.

4. Singh, R.B.; Huber, A.H. Sensitivity Analysis and Evaluation of MicroFacCO: a Microscale Motor Vehicle Emission Factor Model for CO Emissions; *J. Air & Waste Manage. Assoc.* **2001**, *51*, 1087-1099.
5. Singh, R.B.; Huber, A.H. Development of a Microscale Emission Factor Model for CO for Predicting Real-Time Motor Vehicle Emissions; *J. Air & Waste Manage. Assoc.* **2000**, *50*, 1980-1991.
6. *AP-42: Compilation of Air Pollutant Emission Factors—Mobile Sources*; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 1998.
7. Meisner, B.N.; Graves, L.F. Apparent Temperature. *Weatherwise* **1985**, *Aug*, 211-213.
8. Koupal, J. *Air Conditioning Correction Factors in MOBILE6*, EPA420-R-01-055, MOBILE6 Document Number M6.ACE. 002; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 2001.
9. Singh, R.B.; Colls, J.J. Development and Preliminary Evaluation of a Particulate Matter Emission Factor Model (PMFAC) for European Motor Vehicles; *J. Air & Waste Manage. Assoc.* **2000**, *50*, 1805-1817.
10. Gertler, A.W.; Gillies, J.A.; Pierson, W.R.; Rogers, C.F.; Sagebiel, J.C.; Abu-Allaban, M.; Coulombe, W.; Tarnay, L.; Cahill T.A. *Ambient Sampling of Diesel Particulate Matter*, Draft Final Report; Desert Research Institute: Reno, NV, 2000.
11. Gertler, A.W. Desert Research Institute, Reno, NV. Personal Communication, 2001.
12. Gertler, A.W.; Sagebiel, J.C.; Wittorf, D.N.; Pierson, W.R.; Dippel, W.A.; Freeman, D.; Sheetz, L. *Vehicle Emissions in Five Urban Tunnels*, CRC Project No. E-5; Coordinating Research Council; Prepared by Desert Research Institute: Reno, NV, 1997.
13. Nickling, W.G.; Gillies, J.A. Emissions of fine-grained particulate from desert soils. In *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*; Leinen, M.; Sarnthein, M., Eds.; Kluwer Academic: Dordrecht, Netherlands, 1989; pp 133-165.
14. Nickling, W.G.; Gillies, J.A. Dust Emissions and Transport in Mali, West Africa; *Sedimentology* **1993**, *40*, 859-868.
15. Nickling, W.G.; Lanvaster, N.J.; Gillies, J.A. *Field Wind Tunnel Studies of Relations between Vegetation Cover and Dust Emissions at Owens Lake*; Interim Report Prepared for the Great Basin Unified Air Pollution Control District by the University of Guelph, Guelph, Ontario, Canada, and Desert Research Institute, Reno, NV, May 8, 1997.
16. White, B.R.; Cho, H.M.; Kim, D.S. *Final Technical Report to Great Basin Unified Air Pollution Control District*, Contract No. C9464; Department of Mechanical and Aeronautical Engineering, University of California, Davis: Davis, CA, 1997.
17. Cahill, T.A.; Goodart, C.; Nelson, J.W.; Eldred, R.A.; Nasstrom, J.S.; Feeney, P.J. Design and Evaluation of the DRUM Impactor. In *Proceedings of the International Symposium on Particulate and Multiphase Processes, Volume 2: Contamination Analysis and Control*; Ariman, T.; Veziroglu, T.N., Eds.; Hemisphere Publishing Corp.: Washington, DC, 1985.

About the Authors

Dr. Rakesh B. Singh was a National Research Council Research Associate at the National Exposure Research Laboratory, EPA. Currently, he is an independent contractor. Alan H. Huber is with the National Oceanic and Atmospheric Administration in partnership with the National Exposure Research Laboratory. James N. Braddock is with the National Exposure Research Laboratory. Address correspondence to: Alan H. Huber, National Oceanic and Atmospheric Administration and U.S. Environmental Protection Agency, US EPA NERL, Mail Code E243-03, Research Triangle Park, NC 27711; phone: +1-919-541-1338; fax: +1-919-541-1379; e-mail: huber.alan@epa.gov.